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Determining the Impact of Meteorological Assimilation Data Ingest System (MADIS) Observations on Weather Research and Forecasting (WRF) Forecasts Utilizing National Center for Atmospheric Research's (NCAR's) Forecast Sensitivity to Observations Software Package

by Stephen F. Kirby

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14. ABSTRACT

The National Center for Atmospheric Research's (NCAR's) Forecast Sensitivity to Observations software is employed to determine the impact of both surface and upper-air observations on Weather Research and Forecasting (WRF) forecasts during early February 2012. Scripts were engineered to execute both the WRF Preprocessing System and WRF code modules in order to generate 12- and 24-h forecasts. These forecasts served as input for the generation of a regional background error (BE) covariance tuned to the timeframe and region of interest, the southwestern U.S. This new BE covariance was used in a sensitivity study to determine the impact of observations on the WRF forecast. Observation types included surface observations such as mesonet, meteorological terminal aviation routine weather report (METAR), and ship reports while the upper-air observations included profiler, balloon soundings, satellite, and pilot reports.

15. SUBJECT TERMS

forecast sensitivity to observations, WRF preprocessing system, weather research and forecasting model, data assimilation

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Preface

The National Center for Atmospheric Research (NCAR) has developed a software suite that comprises their “Forecast Sensitivity to Observations” (FSO) package and is utilized in order to determine the impact of observations (spanning the surface and upper atmosphere) on forecasts produced from the Weather Research and Forecasting (WRF) model (version 3.4.1). FSO is composed of the Weather Research and Forecasting (Model)—Advanced Research WRF (WRF-ARW), the WRF-ARW tangent-linear and adjoint models (jointly called WRFPLUS in the FSO paradigm), and the WRF Variational Data Assimilation (WRFDA) System.

A study using FSO to discern the impact of observations on the WRF forecast is discussed. The area of concern is the southwestern United States with the time period analyzed being early February 2012. FSO uses a background error (BE) covariance matrix, and for this study, a new one is generated for this particular domain/timeframe.

Global Forecast System (GFS) model data acquired from the National Centers for Environmental Prediction (NCEP) provides the initial conditions for the WRF forecasts.

Observations, including mesonet, meteorological terminal aviation routine weather report (METAR), surface aviation observation (SAO), radiometer, satellite (polar-orbiting), ship, aircraft communications addressing and reporting system (ACARS), rawinsonde observation (RAOB), and profiler are obtained from the Meteorological Assimilation Data Ingest System (MADIS) File Transfer Protocol (FTP) servers. MADIS is run operationally by the National Weather Service (NWS) (https://madis-data.nws.noaa.gov/).

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1. Summary

To ascertain which types of meteorological observations are most beneficial to the Weather Research and Forecasting (WRF) forecast used in Army applications, the National Center for Atmospheric Research (NCAR)'s Forecast Sensitivity to Observations (FSO) software suite is employed for a case study encompassing the southwestern United States. FSO is composed of Weather Research and Forecasting (Model)—Advanced Research WRF (WRF-ARW) (version 3.4.1), the WRF-ARW tangent-linear and adjoint code (jointly called WRFPLUS in the FSO paradigm), and the WRF Variational Data Assimilation (WRFDA) System (*1*, *2*, *3*, *4*).

The Global Forecast System (GFS) data, acquired from the National Centers for Environmental Prediction (NCEP) provides the initial conditions for the WRF model. Observations for this study were obtained from the Meteorological Assimilation Data Ingest System (MADIS) data servers (*5*) maintained by the National Weather Service (NWS) and include surface data, such as mesonet and meteorological terminal aviation routine weather report (METAR), as well as data sets that characterize the upper regions of the atmosphere, including rawindondes, profiler, satellite, etc.

FSO requires a WRF background error (BE) covariance; one can either employ the "global" BE covariance dataset supplied with the FSO package or derive their own, tuned to a particular domain of interest and time period. For this study, an initial FSO case was run for February 7, 2012, 1200 Greenwich Mean Time (GMT), using the global BE covariance dataset. The test indicated that some of the observations had a deleterious effect on the forecast for this time, which provided the impetus to create scripts that allow the user to generate a 1-month (or longer) set of WRF forecasts to be used to develop a BE covariance tuned both temporally and geographically. The scripts run WRF Preprocessing System (WPS) and WRF, for a period and location of the user's choosing, generating the T+12- and T+24-h forecasts for each day beginning at 0000 GMT and 1200 GMT. An NCAR script, "gen_be_wrapper.ksh", then examines the differences between the 12- and 24-h forecasts, valid at the same time, to generate the BE covariance file. The WRFDA user's guide recommends a WRF forecast dataset spanning at least 1 month (*6*); for this study, a period of approximately 5 weeks of WRF forecasts was used as input to the BE covariance calculation. For the following test periods, (1) 2012020112-2012020200, (2) 2012020212-2012020300, (3) 2012020312-2012020400, the newly derived "local" covariance was employed. For case (1) only the ship observations impacted the WRF forecast positively, at 2012020200. For case (2) the only negative impact on the WRF forecast was noted at 2012020212, caused by aircraft reports (AIREP), while for case (3) the only negative impact was caused by ship reports at 2012020312.

2. Introduction

For the purposes of Army weather applications, where the areal and temporal extent of available observations may be limited, it is imperative that modelers be able to determine which observations will most positively influence the forecast. To this end, this report illustrates a methodology, whereby a user can generate the long period (> = 1 month) of WRF forecasts required to create a BE covariance matrix that is representative of the area of interest both in time and space. An example of such a regionally and temporally tuned BE covariance matrix is employed in a case study outlined in this report to determine its efficacy when applied in FSO. The impact of MADIS observations on WRF forecasts over the period February 1–4, 2012, in the southwestern U.S. is discussed.

NCAR's FSO software suite consists of:

1. WRF-ARW (version 3.4.1)–WRF-ARW is a weather forecasting model (also termed a "forward" model) intended for mesoscale size domains.

2. WRF-ARW tangent-linear–The tangent-linear model (TLM) is derived from the forward model (WRF-ARW). A TLM provides a first-order approximation to the evolution of perturbations in a nonlinear forecast trajectory (*7*).

3. WRF-ARW adjoint model–The WRF adjoint is the transpose of the WRF TLM. The transpose, in terms of code, will cause for example, an inner nest subroutine to become an outer nest subroutine. Thus, when the WRF adjoint is executed it runs in reverse.

   > "Unlike a forward model which forecasts temperatures, winds, humidities and the like forward in time from a presumed known state, the adjoint propagates sensitivities with respect to those fields, as well as model parameters, backwards in time from a specified "final" sensitivity condition designed to test one's hypothesis. The adjoint is the transpose of the "tangent linear model", itself a forward integrated model linearized about the temporally and spatially varying state provided by the control simulation under scrutiny." (*8*)

4. WRFDA–This component enables combining observations with WRF model output with the goal to provide the truest snapshot of the atmosphere possible.

3. Background

3.1 A General Cost Function

WRFDA ". . . methods compute the analysis as the model state that minimizes a cost function measuring the fit to the observations and to the background, where the two terms are weighted by the inverses of the observation and background-error covariances, respectively." (*9*) Note the cost function, exemplified by "J," in equation 1. $J[x(t_0)]$ is a function of the state vector $x(t_0)$, which represents the current estimate of the true atmospheric state. The goal is to determine the initial conditions of the model, $x(t_0)$, so to minimize $J. J[x(t_0)]$ signifies a measure of the simultaneous gap between $x(t_0)$ and two independent 'snapshots' of the atmosphere: observations (consisting of surface, upper air measurements, as well as satellite (e.g., POES) and a WRF model forecast, initialized with the GFS model (*10*).

$$J[x(t_0)] = 1/2[x(t_0) - x^b(t_0)]^T B_0^{-1}[x(t_0) - x^b(t_0)] + 1/2 \sum_{i=0}^{n}(y_i - y_i^0)^T O_i^{-1}(y_i - y_i^0): \qquad (1)$$

$x^b = a\ priori\ background\ field,$

$B_0 = background\ error\ covariance\ matrix,$

$y_i^0 = vector\ of\ observations\ at\ time\ t_i,$

$O_i = observation\ error\ covariance\ matrix,$

$y_i = H[x(t_i)]\ where\ H\ represents\ the\ observation\ operator,$

$x(t_i) = M(t_i, t_0)x(t_0), where\ M\ represents\ the\ forecast\ model.$

Observation operators vary in their functionality depending on the observation type under consideration. For example, given that rawinsondes are direct measurements of model variables, simple interpolation of model variables to the observation locations is required. On the other hand, for Geostationary Orbiting Environmental Satellite (GOES) sounder data, not only is interpolation of model variables to measurement location required, but also radiative transfer codes must be executed in order to convert model variables into radiances (*11*).

3.2 A WRF-Specific Cost Function

For FSO, it is necessary to cast the cost function, "J," in terms of WRF model variables,

$$J = \sum_{i,j,k} 0.5[C_u(u_f - u_a) ** 2 + C_v(v_f - v_a) ** 2 + C_T(T_f - T_a) ** 2 + C_q(q_f - q_a) ** 2 + C_p(p_f - p_a) ** 2], \qquad (2)$$

where

i, j represent particular grid points and k represents a model level

u = the u-component of the wind,

v = the v-component of the wind,

T = temperature,

q = mixing ratio,

p = atmospheric pressure.

Here, the subscript “a” refers to the analysis (i.e., the output from WRFDA), taken to be a true characterization of the atmospheric state, and the subscript “f” refers to the forecast (i.e., output from WRF-ARW) and $C_u, C_{v,} C_T, C_{q,} C_p$ are weighting functions that transform the errors of winds, temperature, humidity, and pressure into units of energy [Jkg^{-1}].

The adjoint model starting condition is, for example,

$$\frac{\partial J}{\partial u_f} = C_u\left(u_f - u_a\right), at\ all\ grid\ points\ (i,j,k), units = Jkg^{-1}m^{-1}s \tag{3}$$

with the ultimate goal being the diagnosis of initial condition sensitivity; and next convert the gradients back into units of energy by combining the winds, temperature, and pressure sensitivities as follows:

$$S_0 = \sum_{i,j,k}[\, C_u^{-1}\left(\frac{\partial J}{\partial u_0}\right) + C_v^{-1}\left(\frac{\partial J}{\partial v_0}\right) + C_T^{-1}\left(\frac{\partial J}{\partial T_0}\right) + C_q^{-1}\left(\frac{\partial J}{\partial q_0}\right) + C_p^{-1}(\frac{\partial J}{\partial p_0})], \tag{4}$$

where $C_u^{-1}, C_v^{-1}, C_t^{-1}, C_q^{-1},$ and C_p^{-1} are inverses of the weighting functions, that transform the sensitivity gradients of winds, temperature, humidity, and pressure into units of energy [Jkg^{-1}], accounting for grid volume size/mass (*12*). These are the units used for the plots in section 6 illustrating observation impacts on the WRF forecast.

3.3 Mathematical Derivation of TLM Code

To illustrate the process of deriving WRF-ARW TLM code from WRF-ARW forward model code, an outline follows:

1. Assume this initial equation is derived from a mesoscale forecast model:

$$y = a + bx + cx^2 + dx^3 + ez^{1/2}\ . \tag{5}$$

2. Take the differential:

$$y' = bx' + 2cxx' + 3dx^2x' + 1/2ez^{-1/2}z'\ . \tag{6}$$

3. Combine constants and terms, to arrive at the forward code:

$$Y = A + Bx + Cx^2 + Dx^3 + E\sqrt{z}\ . \tag{7}$$

4. And, finally, from this forward code, the tangent-linear code may be derived:

$$Y = Bx_{TL} + 2Cxx_{TL} + 3Dx^2x_{TL} + 1/2Ez^{-1/2}z_{TL}\ . \tag{8}$$

3.4 Porting Forward Model Code to TLM Code

Also note that logical tests in the forward model must be carried to the TLM using the active forward model variables (*13*) (see table 1).

Table 1. Model variables: forward and TLM examples.

Forward example:	**TLM example:**

IF (T > 273.) THEN
$Q = T^2$
ELSE
$Q = 2 * T$
ENDIF
	IF (T > 273.) THEN !NOT T_TLM
	$Q_{TLM} = 2 * T * T\_TLM$
	ELSE
	$Q_{TLM} = 2 * T\_TLM$
	ENDIF

4. Methodology

The steps in the FSO process are as follows:

1. Define a "reference," which is a WRFDA forecast (that includes assimilation of a multitude of data types, including mesonet, rawinsonde observation [RAOB], satellite, etc., plus a background first guess, GFS) yielding a 'best estimate' of the 'true state' of the atmosphere at verification time.

2. Use the adjoint of the WRF to obtain the gradient of the forecast error with respect to the initial state.

3. Apply these steps to the initial conditions both before the analysis is carried out and afterwards. This allows for the determination of the sensitivity of the forecast error at final time relative to the WRF data assimilation at initial time.

4. Use the adjoint of the WRFDA to compute the impact of each observation type on the forecast error reduction (*1*).

4.1 Generating BE Covariance Matrix

To facilitate the dynamic generation of the BE covariance, applicable to one's domain/time period, the author wrote shell scripts which (1) generate the namelist files for the WRF Preprocessing System (WPS), (2) create the initial conditions needed for WRF, and (3) execute the T+12- and T+24-h forecasts for each day. The user supplies a time period and a domain center latitude and longitude. The 12- and 24-h forecasts used in generating the BE covariance cover a period of approximately five weeks. The grid dimensions utilized were 113 × 113 points with a grid resolution of 15.75 km and spanning 41 levels. Lastly, to generate the BE covariance using one's set of WRF forecasts, an NCAR script is used within which one can set the grid size, start and stop times, whether or not recursive filtering is used, etc.

4.2 Converting MADIS Data for Use in FSO

Making the MADIS data ingestible by FSO is a two-step process:

Step 1. The MADIS data is read and converted by NCAR-supplied code (author: Ruifang Li; see http://www.mmm.ucar.edu/sections/data-assimilation.php) that converts the data to "Little-R" format, which essentially is a relic of a data format used in an earlier mesoscale model 5th Generation Mesoscale Model (MM5). The author created a "MASTER" little-r file that is a concatenation of each observation type in date/time order.

Step 2. This Little-R format data is subsequently ingested by an NCAR WRFDA process called "obsproc." This code module not only reformats, but also performs quality control, such as checking for vertical consistency/superadiabatic conditions in a sounding. This results in a file called obs_(date).3DVAR, which may be used by FSO.

4.3 Executing FSO

Running FSO is a three-step process:

Step 1:
a. Run WRFDA for the initial time; this is where the observations are merged with the WRF-ARW forecast to provide the most accurate assessment of the atmosphere possible.
b. Run the update boundary condition code—this is where the WRF lateral boundary conditions are updated to be consistent with the WRFDA analysis.

Step 2: Run the WRF nonlinear and WRF adjoint code.

Step 3. Run the adjoint of the data assimilation using Lanczos minimization; this yields the observation impact on the WRF-ARW forecast.

5. MADIS Data Distribution for This Study

Figures 1–5 are data plots generated via NCAR Command Language (NCL) script, depicting the distribution of data points for one day (February 7, 2012) in this study, for these data types: (1) profiler, (2) Global Positioning System Precipitable Water (GPSPW), (3) soundings, (4) ship reports, and (5) METAR (surface) reports. The data used for this study was obtained from MADIS and is in netCDF format.

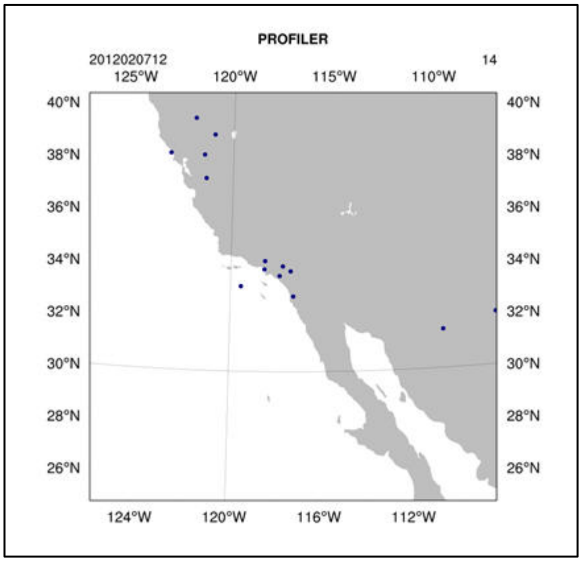

Figure 1. Distribution of profiler reporting sites, February 7, 2012.

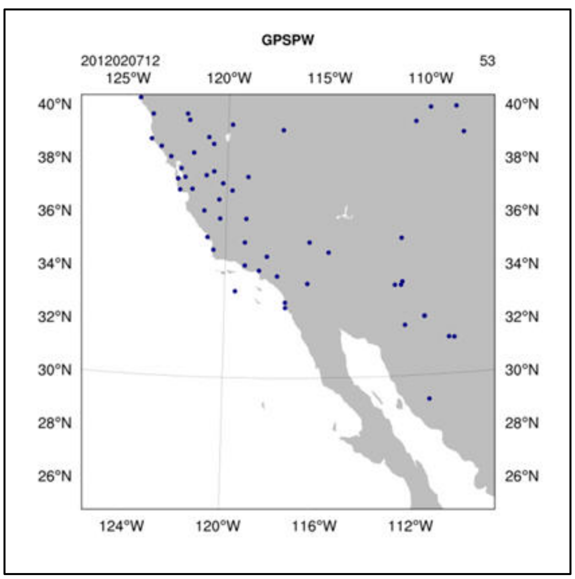

Figure 2. Distribution of Global Positioning System (GPS) derived Precipitable Water reporting sites.

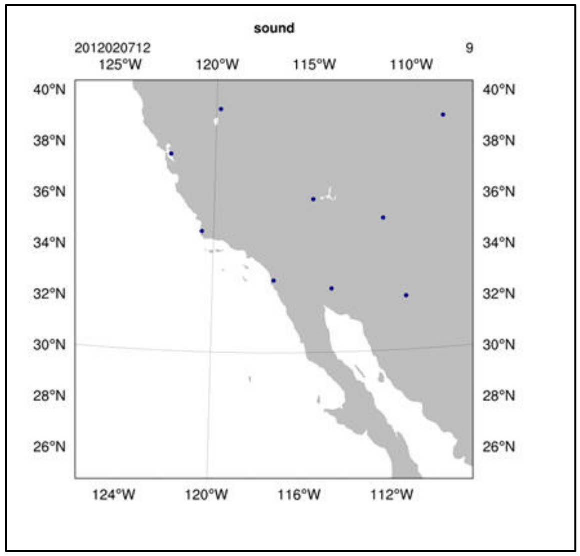

Figure 3. Sounding (balloon) sites.

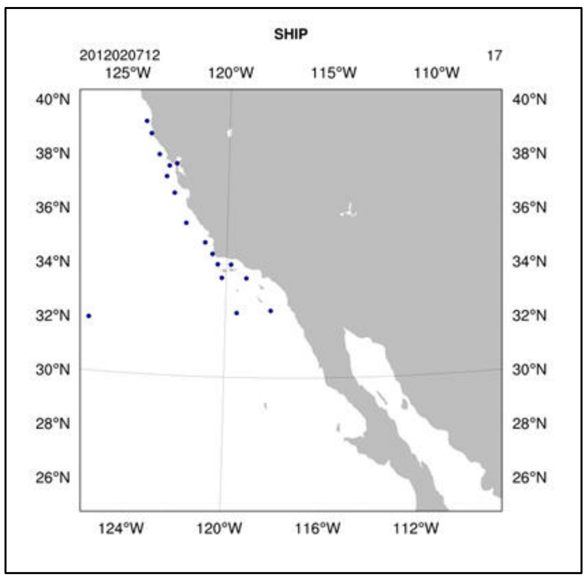

Figure 4. Ship reports distribution.

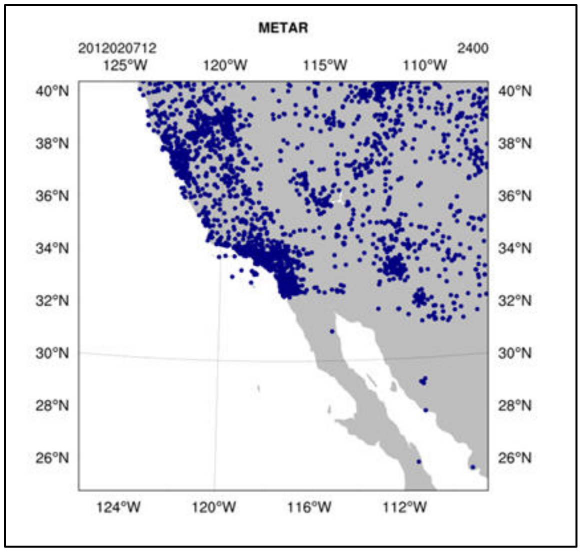

Figure 5. METAR (surface reports) distribution.

6. FSO Case Study Results

An initial FSO case was run for February 7, 2012 encompassing the geographical area seen in figures 1–5. The NCEP global BE covariance was used and the results indicated that the observations were not making the positive impact expected. For this case, the “CV3 be.dat” file, representing BE covariance was used. According to Chapter 6 of the *NCAR WRFVAR User’s Manual*:

> “CV3 is the NCEP background error covariance (and) is estimated in grid space by what has become known as the NMC method. The statistics are estimated with the differences of 24- and 48-hour GFS forecasts with T170 resolution valid at the same time for 357 cases distributed over a period of one year. Both the amplitudes and the scales of the background error have to be tuned to represent the forecast error in the guess fields.” (*14*)

It is not clear whether the use of this ‘generic’ global BE covariance matrix attributed to the issues previously described. A large number of test cases comparing the use of the global BE versus a “local” BE would be required to distinguish that. Nonetheless, the author created shell scripts as a means of generating a BE covariance dataset tuned for the area of interest and timeframe of this study. When supplied with start/stop date/time values and a domain centerpoint, the scripts generate WRF output files for that period, containing the T+12-h and T+24-h forecasts for each day starting at 0000 GMT and 1200 GMT. These forecast datasets then serve as input to the NCAR “gen_be” utility. This utility examines the differences between the 12- and 24-hour forecasts valid at the same time. With this new application, a user will be able to generate a BE covariance tuned to their particular domain.

Figures 6–21 depict what effect the observations had on the WRF-ARW forecast. Negative values (units are J/kg), indicate a positive impact on the forecast, i.e., they reduced forecast error. Average impacts over the whole forecast period, 2012020212–2012020400 are displayed, as well as time-series plots for a given observation type. Also, for soundings, vertical impact is illustrated.

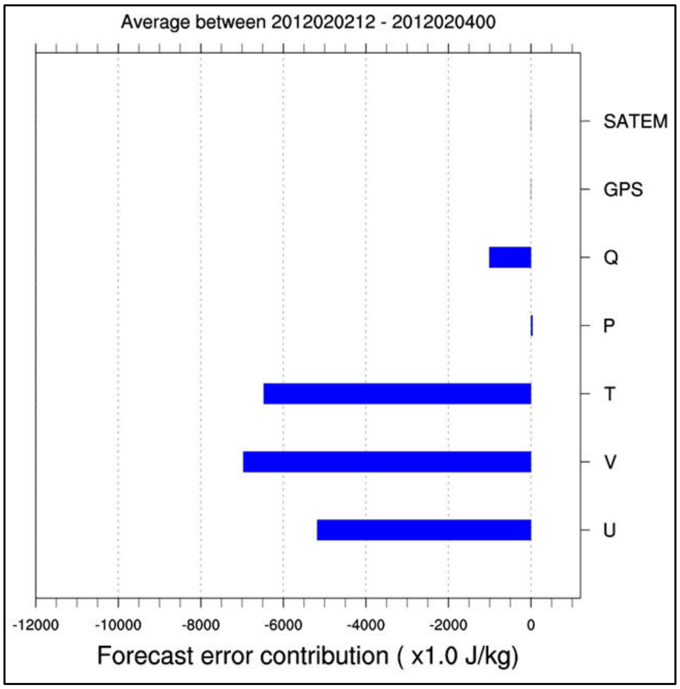

Figure 6. A depiction of the impacts of various components of the observations on the WRF-ARW forecast for the period February 2–4, 2012. A negative forecast error contribution value indicates the observation reduced forecast error.

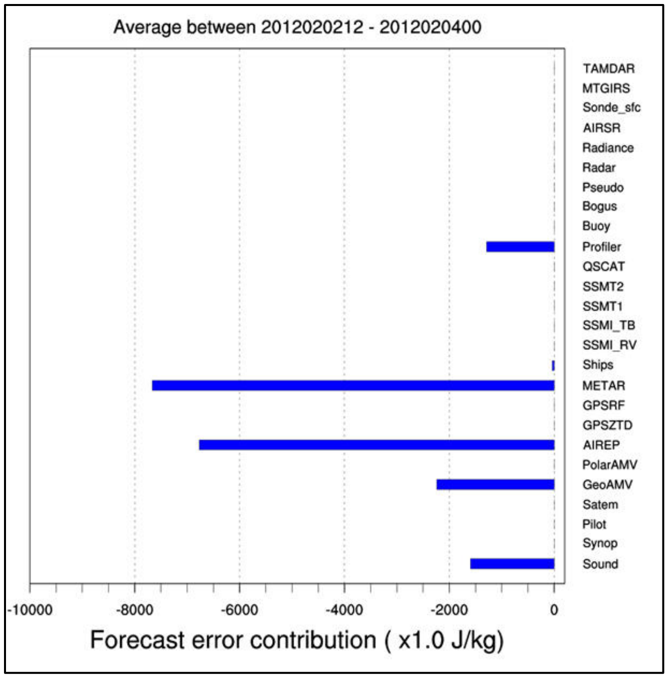

Figure 7. The impacts of various observation types on the WRF-ARW forecast. METAR and airline reports have the greatest impact.

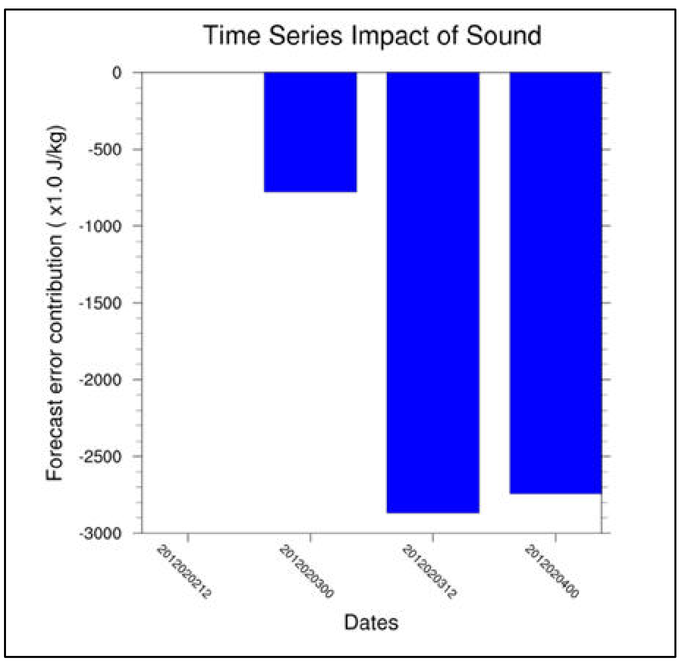

Figure 8. A time series depicting the impact of balloon soundings on the WRF-ARW forecast between February 2–4, 2012.

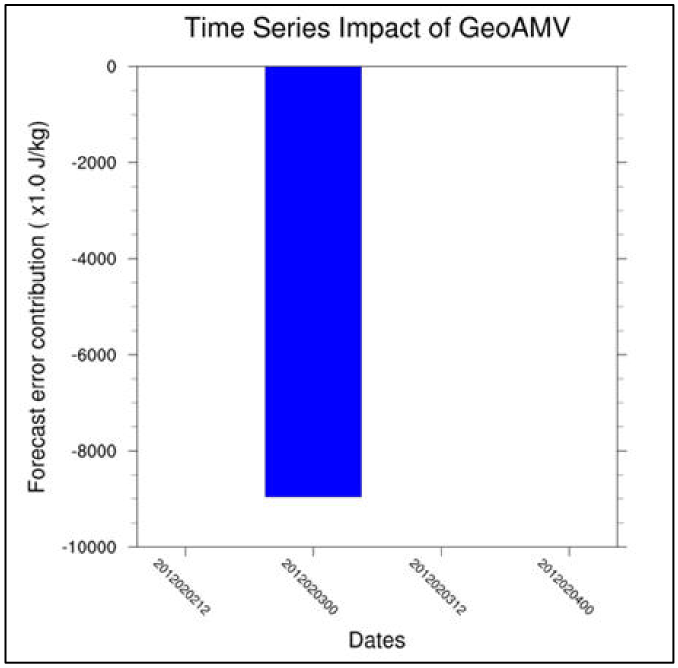

Figure 9. Satellite “atmospheric motion vectors” impact on the WRF-ARW forecast.

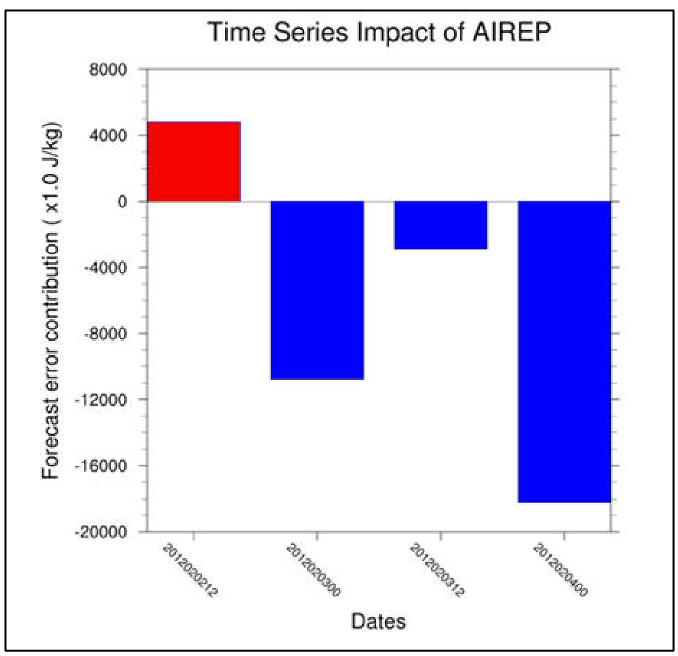

Figure 10. Airline reports impact on the WRF-ARW forecast depicted in time series. The red block at 2012020212 indicates the reports reduced forecast accuracy for the first time period.

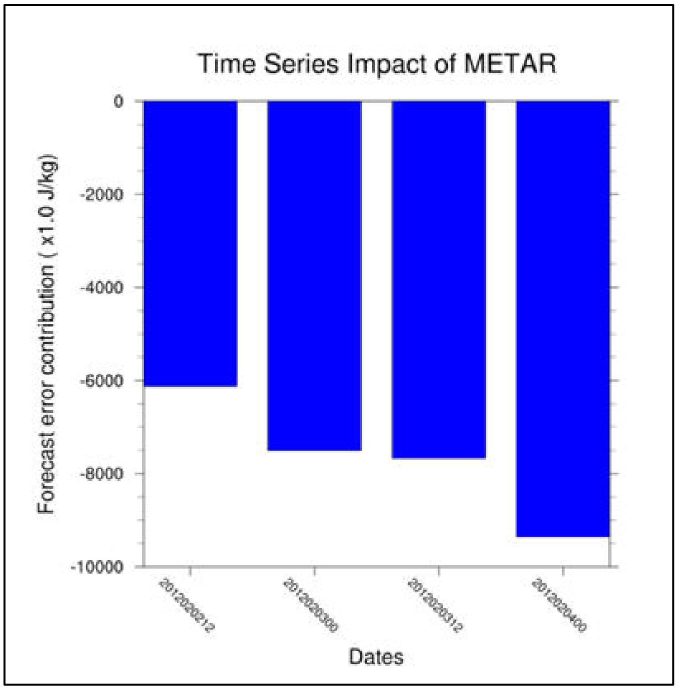

Figure 11. Time series depiction of the impact of surface reports on the WRF-ARW forecast. Note how the observations incrementally reduce forecast error as the forecast proceeds.

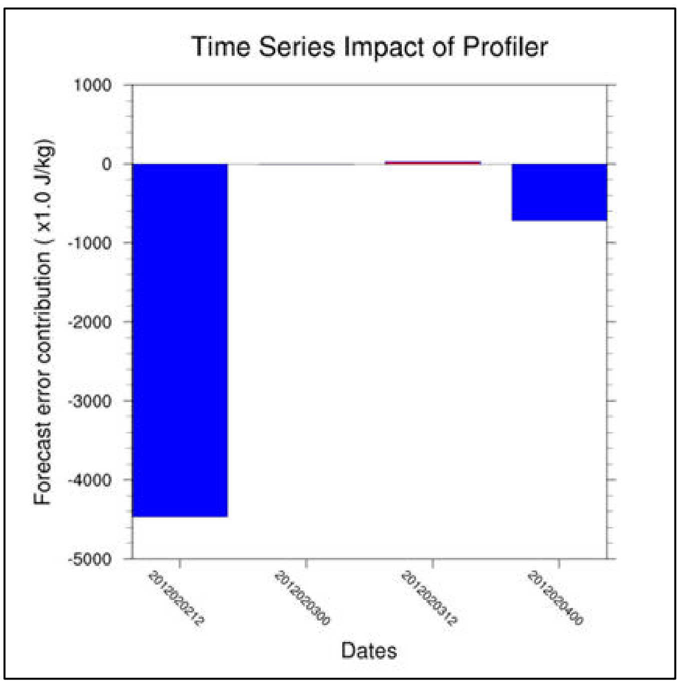

Figure 12. Impact of profiler reports as the WRF-ARW forecast progresses. Note the impact is negligible for forecast periods 2 and 3.

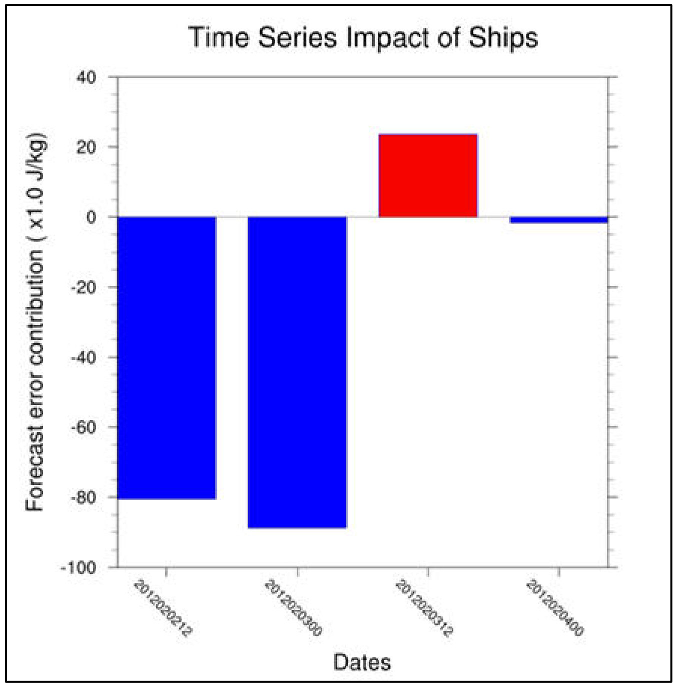

Figure 13. Impact of ship reports on the forecast. The forecast is degraded by the ship reports in period 3.

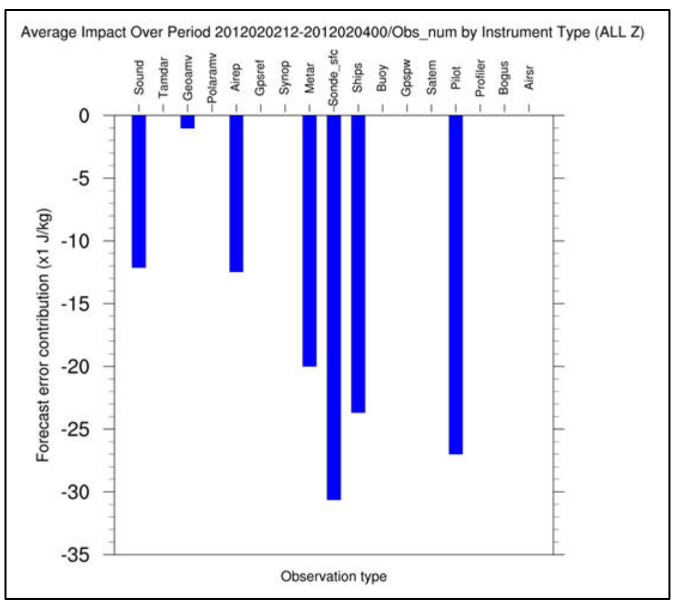

Figure 14. A depiction of the average impact over the whole WRF-ARW forecast period, and at all model levels for each observation type as a function of the number of observations taken. The surface portion of the soundings and pilot reports have the greatest impact.

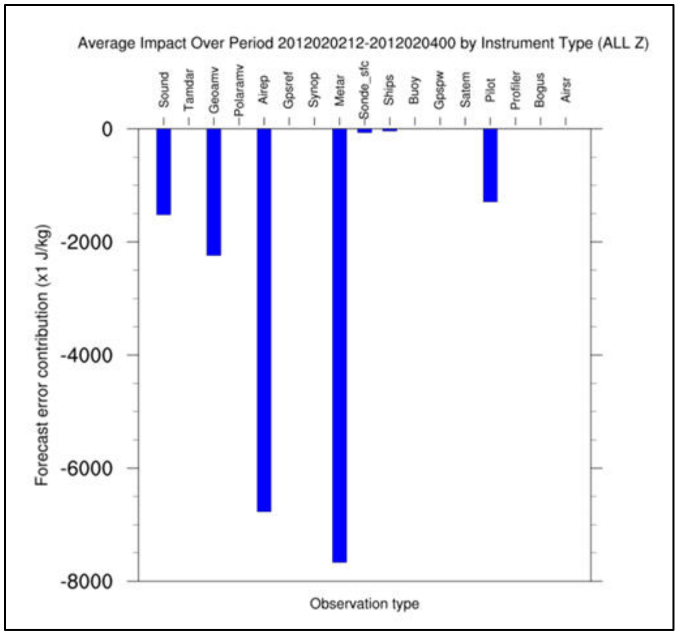

Figure 15. Impact of each observation type averaged over the whole forecast period. METAR imparts the most improvement on the forecast.

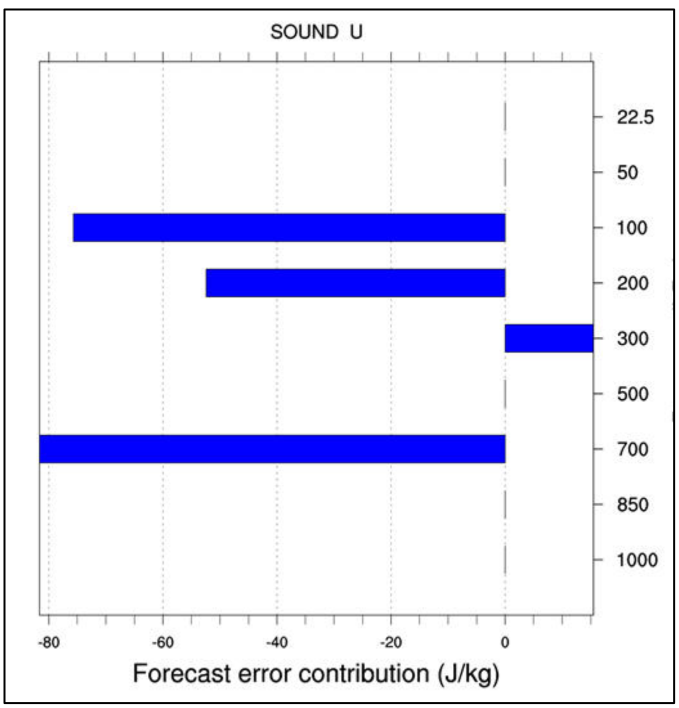

Figure 16. A depiction of the sounding’s u-component impact as a function of atmospheric height level for the period 2012020212–2012020400. Note the negative impact on the forecast at 300 mb.

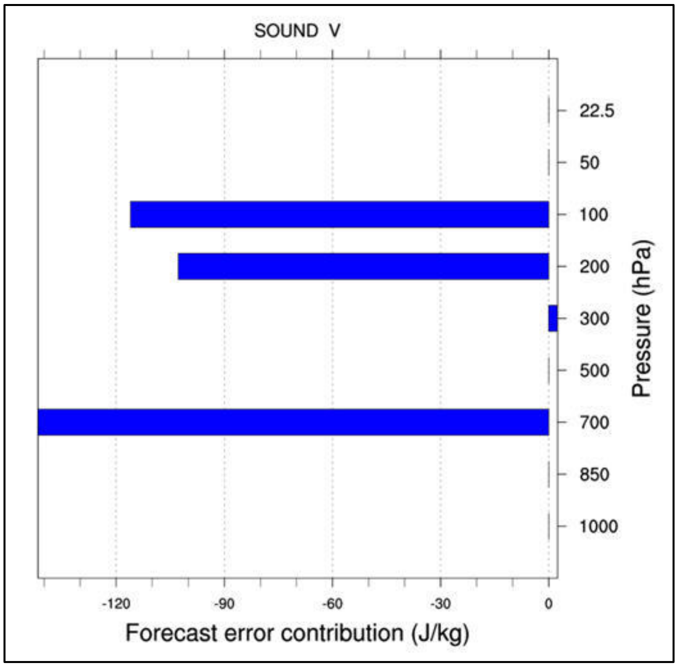

Figure 17. Impact of sounding's v-component on the WRF forecast as a function of height. Note the slight negative impact on the forecast at 500 and 300 mb.

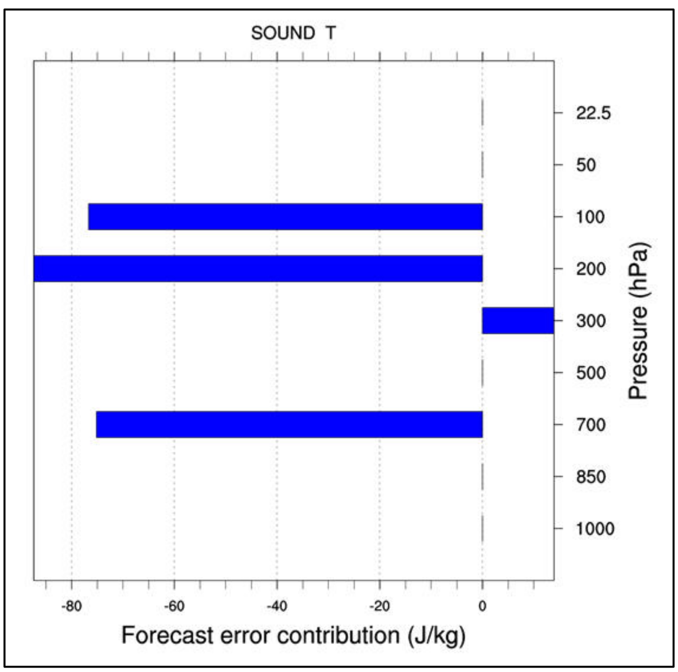

Figure 18. Impact of sounding temperature on WRF forecast as a function of height. Again, negative impact at 300 mb is noted.

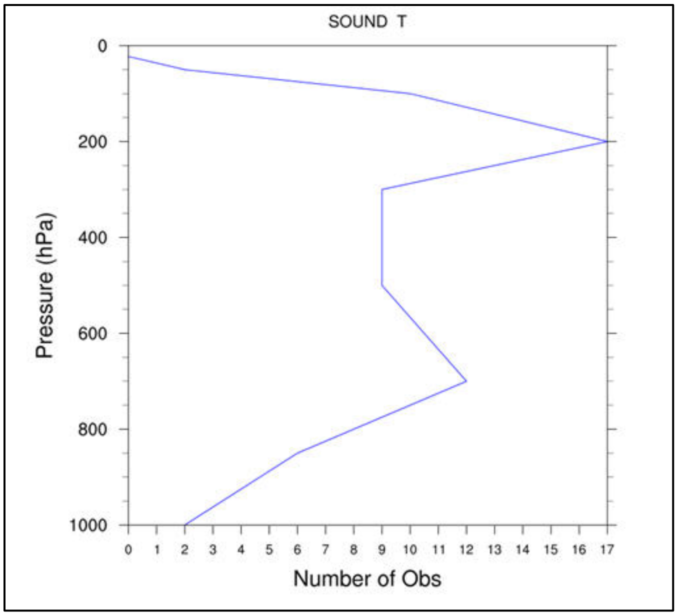

Figure 19. The number of sounding temperature observations as a function of height.

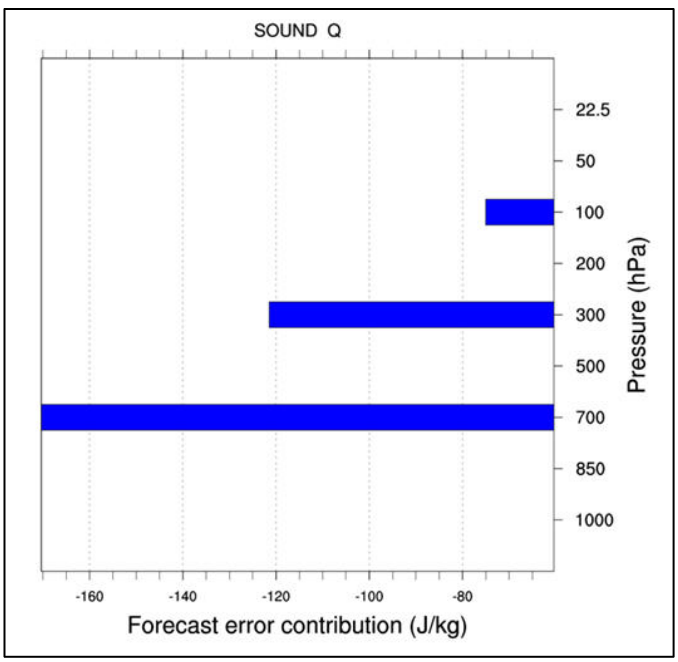

Figure 20. The impact of sounding mixing ratio on the WRF forecast as a function of height.

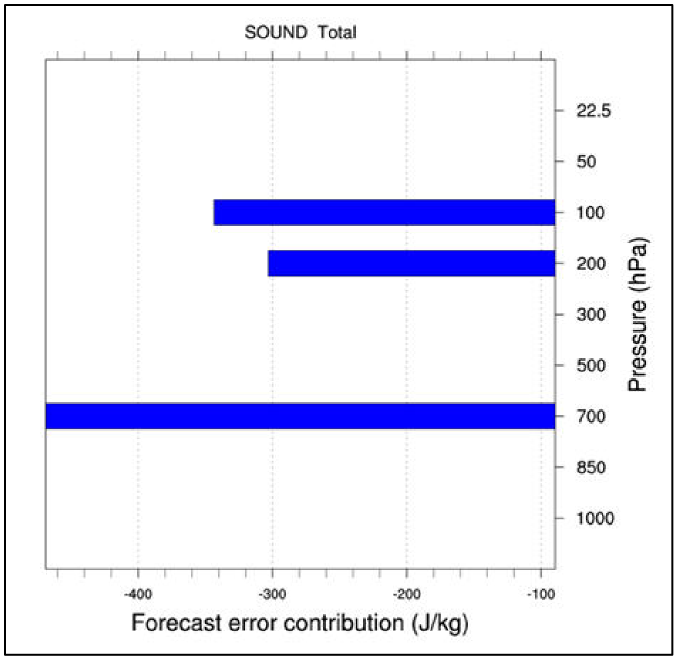

Figure 21. Depiction of the combined impact of soundings on the WRF forecast as a function of height. The greatest impact is noted at 700 mb.

7. Conclusions

The development of an automated means to generate the long-term span of WRF forecasts (> = 1 month) described in this report provides a means for generating a BE covariance matrix, required by FSO, that is representative of the time period and domain of interest. NCAR FSO is an excellent tool to determine the impact of MADIS observations on a WRF forecast and may help forecasters in the field, who may be limited in what observations are available, due to time or tactical constraints, etc.

For this particular study, METAR, airline reports, and the surface portion of soundings (sonde_sfc) contributed most significantly to improving the WRF-ARW forecast compared to using GFS alone. There were forecast periods when observations degraded the forecast (e.g., airline reports at 2012020212 and ship reports at 2012020312) as well as instances where the observations had virtually no impact, for example, profiler at 2012020300 and 2012020312, but overall, observations clearly aided the WRF-ARW forecast.

Of note is the fact that Kalnay et al. (*15*) show in their 2012 paper that one can deduce forecast sensitivity to observations using an ensemble Kalman filter (EnKF) algorithm, obviating the need to involve the adjoint of either the forecast model or the data assimilation scheme. Forecast sensitivity to observations is a fertile study area and contrasting the Kalnay and FSO schemes may be profitable and would involve, in part, comparing the computational expense of running model adjoint(s) versus using an EnKF.

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List of Symbols, Abbreviations and Acronyms

ACARS	aircraft communications addressing and reporting system
AIREP	aircraft reports
BE	background error
EnKF	ensemble Kalman filter
FSO	Forecast Sensitivity to Observations
FTP	File Transfer Protocol
GFS	Global Forecast System
GMT	Greenwich Mean Time
GOES	Geostationary Orbiting Environmental Satellite
GPS	Global Positioning System
GPSPW	Global Positioning System Precipitable Water
MADIS	Meteorological Assimilation Data Ingest System
METAR	meteorological terminal aviation routine weather report
MM5	5th Generation Mesoscale Model
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCL	NCAR Command Language
NWS	National Weather Service
RAOB	rawinsonde observation
SAO	surface aviation observation
TLM	tangent-linear model
WPS	WRF Preprocessing System
WRF	Weather Research and Forecasting
WRF-ARW	Weather Research and Forecasting (Model)—Advanced Research WRF
WRFDA	WRF Variational Data Assimilation (System)
WRFPLUS	Joint name for the WRF-ARW tangent-linear and adjoint models as referred to in the FSO paradigm

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